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Progress Report

January 1, 1993 to February 28, 1993

Visible Light Emitting Materials and Injection Devices

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(I) Molecular Beam Epitaxial Growth (Robert Park)

II-VI Work: A method to monitor the free-hole concentration in p-type ZnSe:N in real-time during epitaxial growth has been developed. The method involves quantifying the cathodoluminescence (CL) intensity generated in-situ by virtue of an impinging electron beam which is normally employed to observe reflection high energy electron diffraction (RHEED) patterns during crystal growth. We had shown previously that the CL intensity detected during the growth of n-type ZnSe was directly proportional to the free-electron concentration measured at room temperature. In this work we have developed a more sophisticated detection system involving imaging the CL emission via a CCD camera and subsequently quantifying the intensity of the imaged spot. We have found that the CL intensity (and therefore the free-hole concentration) recorded from p-type ZnSe:N epilayers during MBE growth is a strong function of various parameters including rf power to the source, N_2 background pressure (and therefore N_2 flow rate) and substrate temperature. Since these parameters can be adjusted in real-time, we can employ this in-situ monitoring technique to maximize the free-hole concentration in ZnSe:N material through an optimization process. Such optimization experiments are underway. Also underway is an effort to correlate the CL intensities recorded at the growth temperature with low temperature PL spectra. Ultimately we will calibrate CL intensity against measured free-hole concentrations.

III-V Work: We have continued to make progress in our efforts to grow relatively thick purely zincblende GaN epilayers on βSiC-coated Si substrates by MBE. Single-crystal GaN films as thick as 0.5μm have been grown thus far. By adjusting our Ga flux level, we have been able to achieve GaN growth rates as high as 1Å /S. Surface morphologies at these high rates, however, appear to be poor as observed in the SEM which correlates with our RHEED pattern observations (spotty diffraction patterns). Work is in progress to improve on these morphologies and also to extend the thickness over which purely zincblende GaN films can be grown.

(II) MOCVD Growth (Tim Anderson)

Progress was made in the growth of lattice-matched pseudobinary Zn-Cd-S epilayer material on (100) GaAs substrates as a first step towards growing the novel Zn-Cd-S-Se confinement structures. Close lattice-matched Zn(1-x)Cd(x)S (x=0.58) has been achieved under particular growth conditions in the mass transfer limited region using DMCd, DEZn, and H2S as precursors.

In-situ GaAs surface cleaning by thermal treatment under a reducing environment with hydrogen flow was optimized and the surface morphology of epilayers grown on the substrates that were cleaned at 620 C for 15 minutes were found to be uniform, shiny and specular. But, the substrates cleaned at < 600 C resulted in the growth of epilayers of poor surface morphology with extremely high concentrations of defects.

The cross sectional TEM and TEM diffraction patterns of the lattice-matched sample indicated a single phase zinc-blende crystal structure (first time ever observed for the MOCVD grown ZnCdS) with some stacking faults and microtwin defects visible along (111) facets of the crystal. For a sample that is Cd rich (x=0.81), the patterns provided inconclusive evidence to suggest a particular kind of crystal structure. At best, the patterns seem to suggest a tetragonal structure or a two phase system composed of both sphalerite and wurtzite. However, the crystal structure is definitely not zinc-blende. From X-ray diffraction, the lattice parameter is stretched out from that of the zinc-blende structure and is perpendicular to the (100) face of the GaAs substrate. This deviation of the lattice parameter may be due the strain caused by incorporating more Cd, a larger atom compared to Zn, into the crystal lattice or because with Cd rich samples, the wurtzite structure is thermodynamically stable and the c-axis is evidently aligned along the (100) direction with respect to the GaAs substrate. Interestingly, this indicates a critical composition where a transition occurs from the zinc-blende at x=0.58 to a non-cubic structure at x=0.81. More studies need to be done to determine this structurally transitional composition.

For the good quality single phase zinc-blende epilayers, the layer thickness was found to be uniform indicated by the SIMS depth profile at different locations of the layer. Also, from Figures 1 and 2, the PL spectra shows maximum peaks at 2.78 eV for room temperature and 2.83 eV (strong blue to purple luminescence) for 10 K measurements. The FWHM is 57 meV and 95 meV for 10 K and room temperature measurements, respectively. There is also minimal deep level effects indicating minimal contamination. Work is in progress to improve on the quality of the zinc-blende ZnCdS epilayers both structurally and optically by performing growths at lower growth rates.

(III) Ohmic Contact Formation (Paul Holloway)

Our study of *ex situ* formation of HgSe ohmic contacts to p-ZnSe continued. We have reacted Hg with both post deposited as well as in situ capped ZnSe wafers. Our results to date suggest that if the Se capping layer is much thicker than 2000 to 3000 Å, the HgSe layer formed on the surface does not form all the way to the interface. Apparently the kinetics of the formation of HgSe from solid Se and vapor Hg are limited by a diffusion mechanism. However, upon raising the temperature of the substrate during deposition, the film becomes non-continuous and very rough (on a microscale). Initially we interpreted the change in surface topography as being driven by capillarity forces, however subsequent analysis suggests that the morphology is controlled by sublimation of Se above substrate temperatures of about 200 °C.

The ability of the HgSe layers to allow current to flow across the contact/p-ZnSe interface is compared in figure 3 to that allowed by a vapor deposited, heat treated Au contact. For this particular sample, the total current through the HgSe contact was not greater, but conduction started at a lower voltage than it did for Au. We are now studying improvements in both the processing of the contact and the quality of the p-ZnSe to allow more current to flow across the interface for operation of the device.

(IV) Microstructural Characterization of Column III Nitride Films (Kevin Jones)

Much of this past quarter has been spent investigating the growth of the III-V nitrides by MOMBE. AlN, GaN and InN films were grown by our collaborators Drs. K. Abernathy, A. Katz and S.J. Pearton at AT&T Bell Laboratories in Murray Hill NJ. A variety of growth conditions, including using low temperature buffer layers and substrates including sapphire and GaAs, were investigated. The goal is to grow epitaxial single crystal films of both hexagonal (wurtzite) and cubic (zinc blende) crystal structure to determine if one structure is better suited for doping than the other. The crystallinity of these various films was investigated by x-ray diffraction, SEM beam rocking experiments and TEM (both plan-view and cross-section, using both diffraction contrast and high resolution imaging and selected area diffraction). The fabrication of TEM samples proved to be very difficult. After several hundred hours of lapping and ion milling trials, procedures were developed for both plan-view and cross-sectional sample preparation. The typical preparation time is now down to around 10- 15 hours per sample.

Preliminary SEM and x-ray measurements of a recent set of GaN/Sapphire samples appeared to indicate a growth regime where high quality single crystal growth of GaN/Sapphire was achieved. Only the basal planes of the hexagonal sapphire and wurtzite GaN were observed in the x-ray diffraction pattern. In addition, the SEM image of the surface was smooth compared to the rough surface we have commonly seen with polycrystalline samples. It took over a month to prepare the TEM samples of this film. Both plan-view and cross-sectional TEM samples were prepared. Observation of these films indicated that rather than forming a single crystal with a high density of defects, the film grew as a series of highly oriented columnar grains with relatively low angle grain boundaries separating the grains. In addition a high density of what appear to be rotational stacking faults parallel to the basal plane occur within the grains. Previous authors have suggested these defects may affect the electrical properties. The difference between the SEM and x-ray results and the TEM results raises an interesting question. Many recent GaN/Sapphire growth studies have relied on in-situ RHEED patterns and ex-situ x-ray diffraction for characterization.. Using both of these methods, the above mentioned film would appear single crystal. It would appear that to expedite studies aimed at optimizing the growth conditions, a correlation between TEM and other characterization techniques need to be established. The correlation should be with a less labor intensive, structurally sensitive method such as high resolution x-ray rocking curve analysis or UV adsorption/reflection. The TEM characterization could then focus on the most promising growth conditions. If growth on sapphire continues to be a priority such correlations may be pursued.

Electrically these films have been found to have a high resistivity. Efforts to dope these films with Sn and Mg during growth have not been successful. The dopant is being incorporated into the crystal based on SIMS results but it is not electrically active. It is possible that these low angle grain boundaries or stacking faults are affecting our efforts to extrinsically dope these films. It is also possible that hydrogen is complexing with the dopant and deactivating it. Further attempts to improve the hexagonal growth (on sapphire) and the cubic growth (on GaAs, GaP and SiC) are in progress, as are continued doping studies.

(V) Optical and Electrical Properties of ZnSe (Joe Simmons)

Our research has continued to focus on 3 tasks: (1) measurements of low temperature PL in support of the materials development effort, (2) development of a facility for time resolved PL measurements for a study of excited carrier dynamics in quantum well structures, and (3) a theoretical analysis of the carrier concentration and carrier mobility in doped semiconductors with the goal of understanding the role of various dopants in the formation of ionized defects.

(1) *PL measurements on novel materials*

We have conduced PL measurements at 10-12°K on p-type doped ZnSe films made by MBE (R. Park) to investigate the effect of heavy dopant concentrations. Results will be reported by R. Park. We have also measured PL at room temperature and 10-12°K on $Zn_xCd_{1-x}S$ films grown by MOCVD (Anderson). These showed relatively good band edge luminescence with little deep level emission. Results will be reported by Anderson.

(2) *Time resolved PL studies*

We have received delivery on a frequency-doubled 200fs Ti-sapphire laser. Preliminary tests show sufficient power for conducting time resolved PL measurements. The detection system will be divided into a fast relaxation measurement (less than 100 picoseconds) and a slower relaxation measurement (100 ps to 100 ns). The fast relaxation measurement will use the method of population mixing to study the relaxation times of photoexcited minority and majority carriers. The slower relaxation equipment consists of a fast diode-boxcar integrator system with a 12GHz digital scope for nanosecond-scale studies. First measurements are anticipated in quantum well structures in April. We are awaiting delivery on several instruments (chopper, optical delay generator).

(3) *Analytical modeling of the carrier concentration and mobility in doped ZnSe films*

A numerical approach tor calculating the full solution to the Boltzman Equation was modified to apply to ZnSe. This approach calculates the full carrier and impurity screening contributions, generally ignored by other investigators, which are, however, essential at high dopant concentrations. Full calculations were conducted both numerically and in closed form for the carrier concentration dependence on temperature and doping level. As reported in the past quarterly report, we discovered that it was necessary to use 2 donor states to model the results of Hall effect measurements on n-type doped films. The model shows excellent agreement with experiment. We also used a numerical model to calculate carrier mobility in the same samples as a function of temperature and dopant concentration (see figure 4). No adjustable parameters were used in the mobility calculations. We used the donor concentrations, acceptor concentrations and donor ionization energies developed for the carrier density calculations. The model showed unexpectedly good agreement with measurements over the wide range of temperatures and dopant concentrations tested. This combination of fits has rarely been achieved before. The mobility is generally only modeled to within an order of magnitude, even in GaAs, which has received much of the past attention. However, our approach has yielded mobilities with much better accuracy. There does remain a small systematic error at high temperatures, where the calculated mobility is higher than the measured values. We are currently examining the source of this deviation and are investigating the possibility of improving the many assumptions which are used in mobility calculations. The results of the current mobility modeling effort are attached. A paper is being written, presenting both the carrier density and mobility calculations.

The modeling work has given us insight into the nature of the semiconductor-metal transition which is observed in heavily doped films. Our approach seems to have uncovered a new way of examining such transitions. We are currently trying to understand its implications.

Over the next quarter, we plan to conduct PL measurements on newly developed GaN films, and quaternary and ternary films from the system ZnMgSeS. This will require detection at shorter wavelengths which can be achieved with our present set up. We plan to set up and test the short pulse laser facility for conducting time resolved PL measurements. We are planning to write up the results of the model study of heavily doped n-type ZnSe for publication.

(VI) Diode Laser Fabrication and Testing (Peter Zory)

Modelling of the relationship between peak optical gain and current density of quantum well lasers was also continued. In addition, we have started an initiative to optimize the processing and packaging of ZnSe-based diode lasers. As reported by 3M at the October '92 Workshop, processing of CdZnSe QW material for diode lasers may have the following effects.

1. The free hole densities in the contacting cap layers grown at 150°C will be reduced significantly during processing and packaging if temperatures higher than 150°C are encountered.
2. Dark-line defect nucleation and/or growth rates may be increased due to the wafer thinning procedures normally used to simplify cleaving into bars.

In order to process/package both 3M and UF diode materials with minimization of the above problems, we have developed a processing and packaging procedure where temperatures are kept below 100°C and "thick" wafers can be cleaved into high quality bars (non-striated facets) with high yield. A scribe and break procedure for separating bars into chips has also been developed.

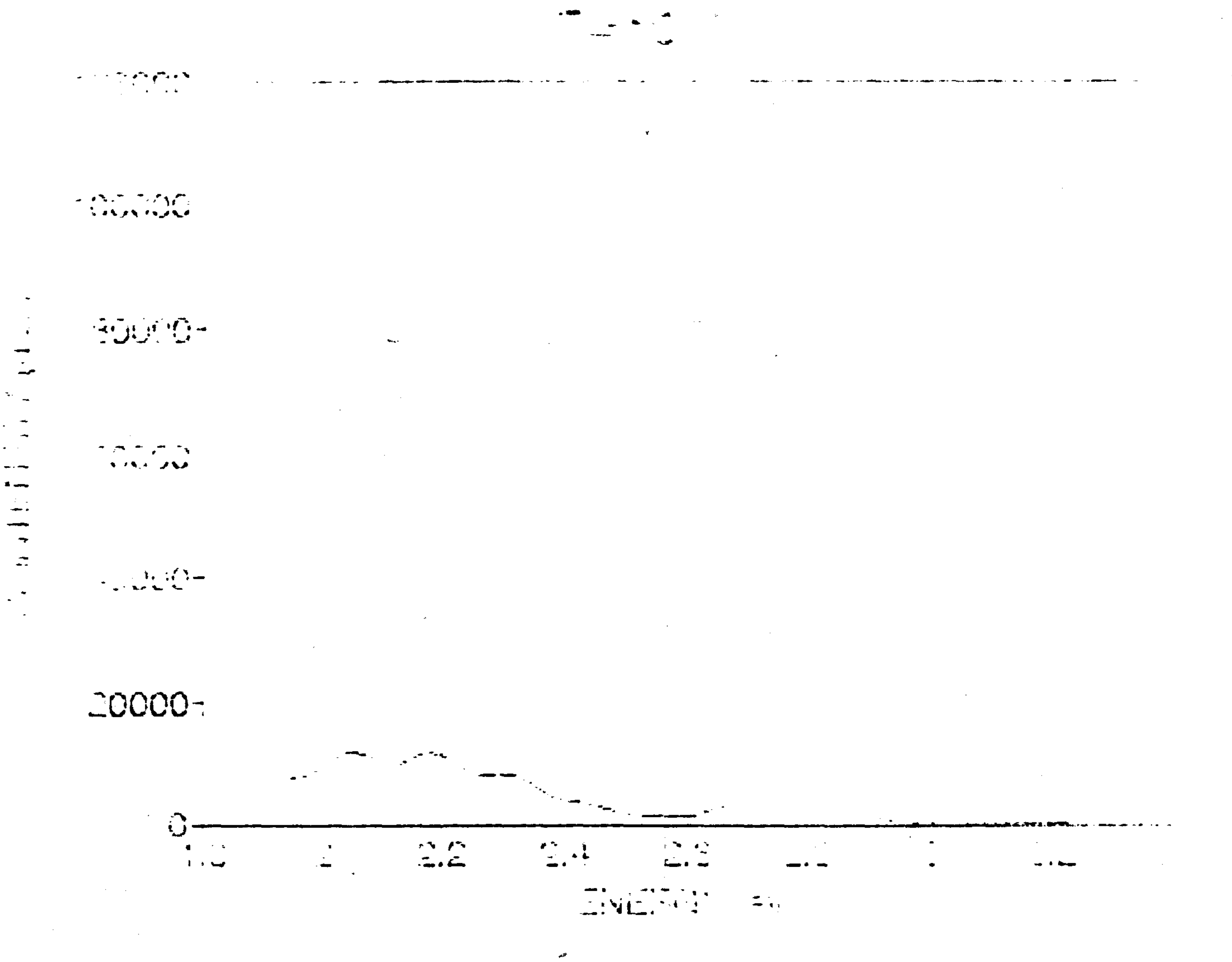

Figure 1 Photoluminescence spectrum at 10 K from ZnCdS.

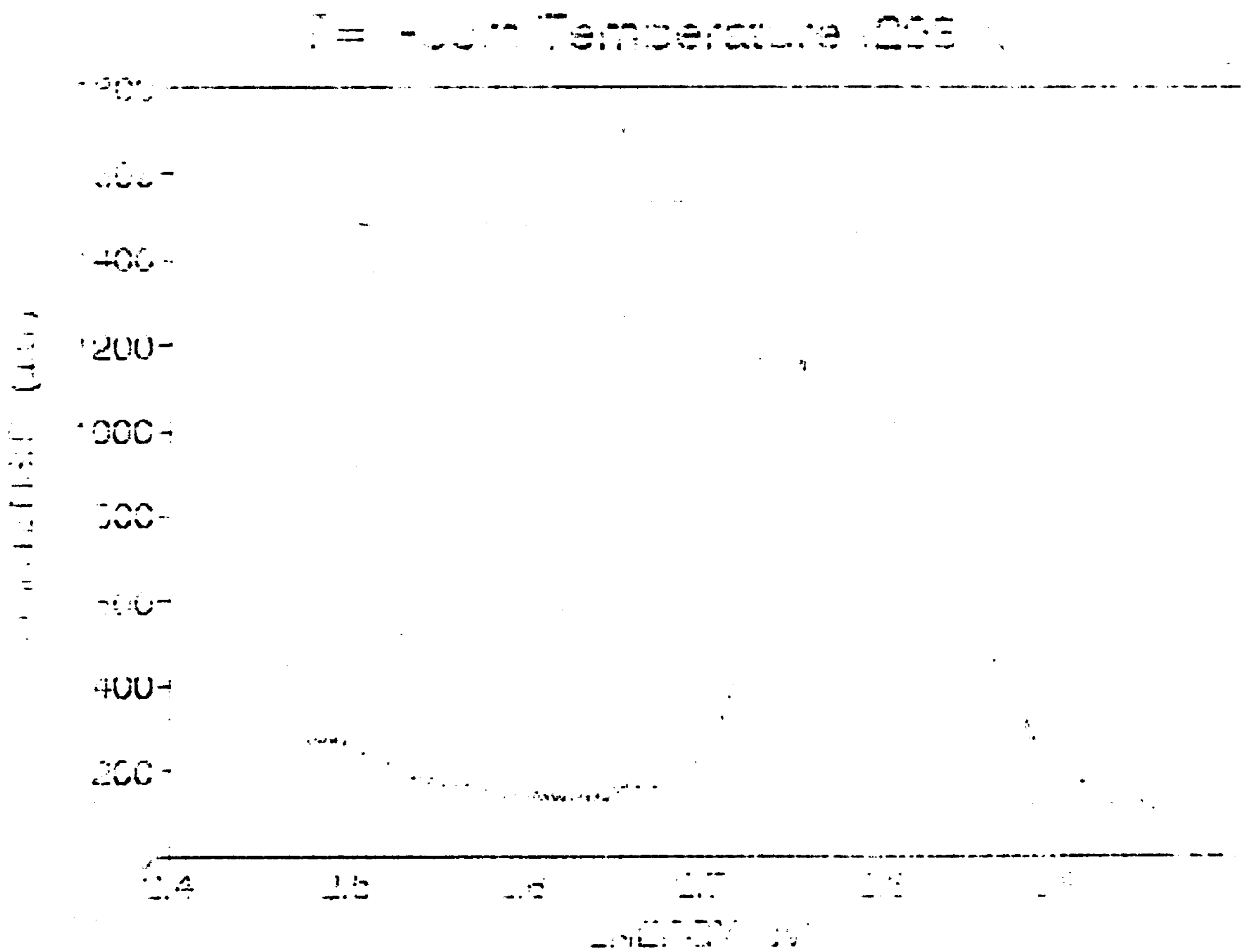

Figure 2 Photoluminescence spectrum at 300 K from ZnCdS.

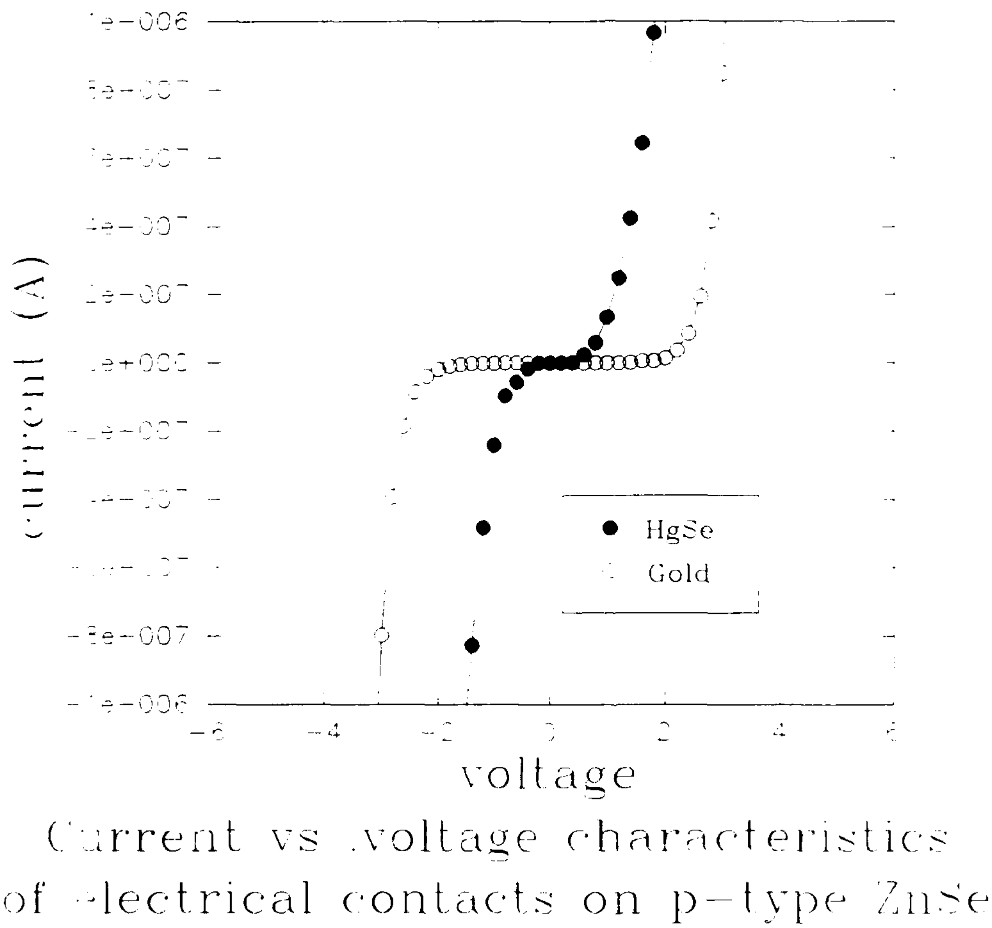

Figure 3 Current versus voltage data from heat treated Au/p-ZnSe contacts and *ex situ* grown HgSe contacts.

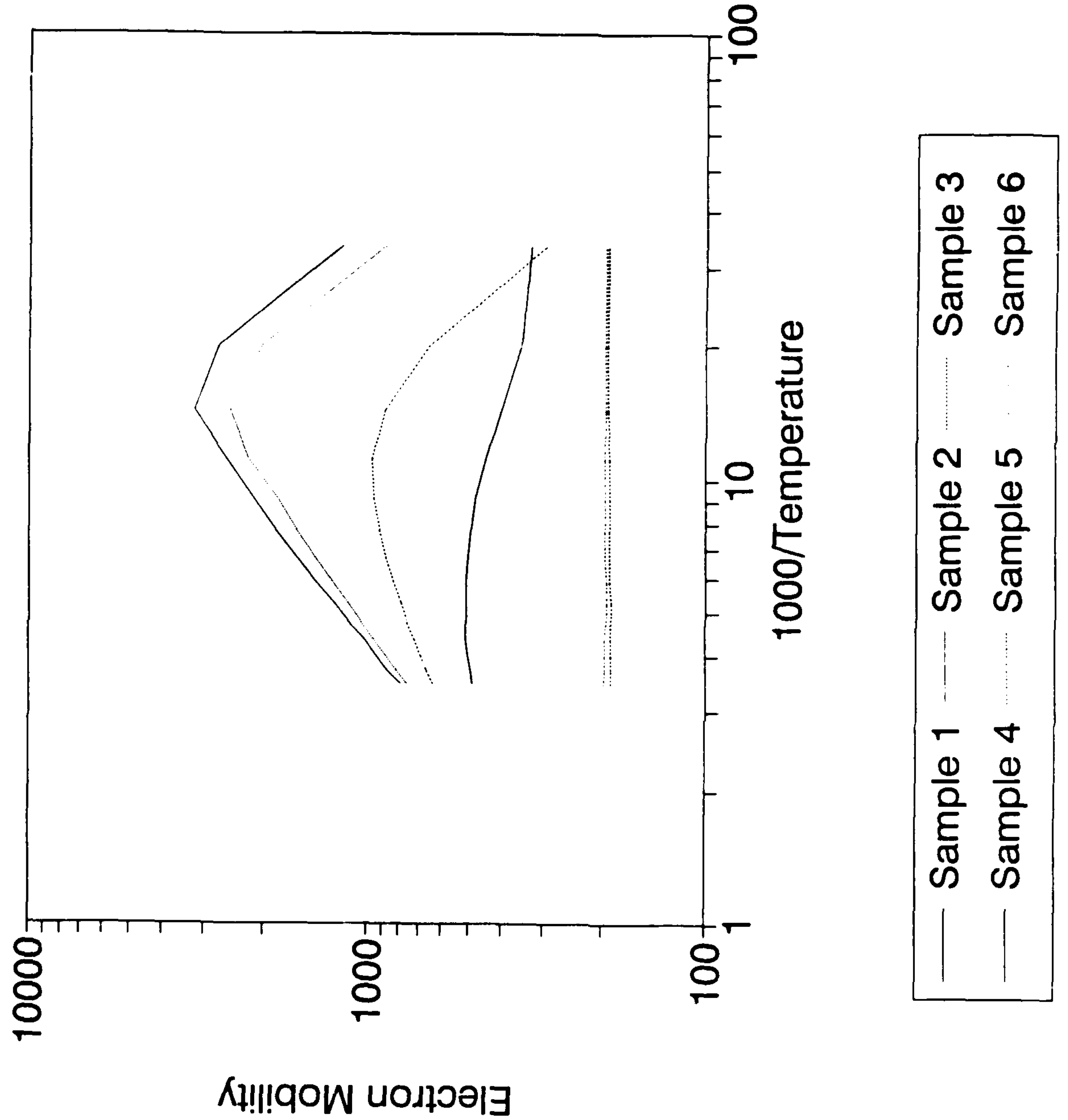

Figure 4 Electron mobility versus inverse temperature for n-ZnSe modelled using two donor states.

(VII) SUBCONTRACT TO COLUMBIA UNIVERSITY (Gertrude Neumark)

Theoretical Calculations for Dopants in ZnSe

PROGRESS REPORT

Dec. 1, 1992 to Feb. 28, 1993

Visible Light Emitting Materials and Injection Devices

ONR/DARPA URI Grant # N0014-92=J-1895

SUBCONTRACT TO COLUMBIA UNIVERSITY (Gertrude Neumark)

Theoretical calculations for dopants in ZnSe

We have continued our work on trying to understand differences, by 3-4 orders of magnitude, in predicted equilibrium solubilities of N and Li in ZnSe between our earlier results [Neumark, Phys. Rev. Lett. 62, 1800 (1989)] and recent first-principles calculations of Van de Walle [e.g. Van de Walle and Laks, J. Lum. 52, 1 (1992), and preprint)]. In this connection, we have worked out a computer program to obtain solubilities, given defect energies and chemical potentials; the Fermi level is here determined self-consistently with the impurity concentrations. As a result, we have also investigated the relations between compensation and solubility aspects of doping in wide-band-gap materials. The overall work is starting to clarify the origins of the discrepancy. The present results are still somewhat tentative (we are estimating possible error limits on the calculations), but actual obtainable equilibrium carrier concentrations, for ZnSe:N, are likely to be in the 10^{17} to $10^{18}/cm^3$ range.

The above work, together with corroborating experimental evidence from our literature survey, is being prepared for presentation at an invited talk at the American Physical Society meeting in March 1993.

Graduate Research Assistants
C. Kothandaraman with Gertrude Neumark

Post-Doctoral Associates
Guan-Jiun Yi, with Gertrude Neumark (through 4/30/93)

(VIII) SUBCONTRACT TO OREGON GRADUATE INSTITUTE OF SCIENCE AND TECHNOLOGY (Reinhart Engelmann)

Gain Modeling in II-VI Strained-Layer QW Structures

1. Gain Modeling

After our previous investigation on different material systems for possible improvement of the performance of the blue green diode laser operating at room temperature, we turn now to the detailed gain modeling study of these devices. The relationships between gain, current, and injected carrier density in these devices are highly structure dependent and therefore provide invaluable insight for device design.

At this stage we are interested in three types of devices, which are diode laser structures based on ZnCdSe/ZnSe (lattice matched to GaAs), ZnSe/MgZnSSe (lattice matched to GaAs) and MgZnSeTe (lattice matched to CdSe). The goal of our studies is to arrive at a flexible modeling program that allows to elucidate trends in a large parameter space and can be easily applied to a variety of different material systems, rather than a sophisticated procedure that generates highly accurate data for specialized situations. Hence, we adopted a simplified theoretical approach to the gain/current calculations [1,2].

In this simplified approach, k selection rules are taken into account as well as the polarization effect for stimulated transition (i.e. TE vs. TM) due to the anisotropy of the QW structure, and intraband scattering of the injected carriers. Band-mixing effects are neglected and effective masses are assumed to be energy independent. Injection induced electrostatic carrier confinement [3] could be considered when the injection level becomes very high for those DH structures with unbalanced carrier confinement.

Another very important parameter for the gain modeling calculation is band offset between active layer and barrier. We have done an intensive literature search on this issue, but only limited data are available for the time being. Trager-Cowan *et al.* have reported a flat valence band in the ZnCdSe/ZnSe system based on photoluminescence data [7]. We think, however, that it is reasonable to assume that a small valence band offset (about 40 meV) is present for our gain modeling studies of this system.

A FORTRAN code based on the above considerations is being written and tested. This new program is mainly based on two codes (one is GNS*.f running on micro-Vax and the other is POLAR supported by HP BASIC 6.2.) which were developed earlier for III-V (InGaAs/GaAs and GaAs/AlGaAs) QW devices [2,3]. It will be designed to be compatible with the new Sun work station which is being set up in the in EEAP Department of OGI.

2. Waveguide Modeling

Wave guide modeling of specialized II-VI device structures is of particular interest for determining the optical confinement factor Γ, an important parameter in diode laser design. As an example, we performed calculations for a MQW $Cd_{0.23}Zn_{0.77}Se/ZnSe$ device structure (100Å/130Å, 10.5 periods, embedded in ZnSe) as described by [8]. The gain confinement factor Γ for the entire MQW layer is 0.74 (summing over all the Γ's of each individual QW layer), which is somewhat higher than the value of a GaAs/AlGaAs laser with the same structure. Fig.1 and Fig.2 show the near field and far field intensity distribution of this device.

3. Plan for Next Period

Detailed gain modeling will be performed for specific device structures in the ZnSe/MgZnSSe material system (lattice-matched to GaAs). The MBE growth of this system is being pursued at the University of Florida (R. Park). Two important questions need to be considered for modifying or improving the gain modeling program of the II-VI compound diode lasers. The first one deals with the strong exciton effects which recently have been observed in the optical properties of ZnSe-based QW's: Are excitons important in the microscopic mechanism responsible for gain and stimulated emission? In another words, are there any departures from the standard degenerate electron-hole pair model which is rooted in standard population inversion calculations? Such an influence has been argued by Ding *et al.* [4], and the answer to this question is controversial. The second one is related to strain effects. So far we have only considered the biaxial-compressively strained QW, while, as O'Reilly *et al.* have demonstrated in III-V QW lasers [5], the lowest threshold current can be obtained through tensile strain. Can we get the same beneficial effect of tensile strain in II-VI devices? One of the advantages of the MgZnSeTe based device is the fact that both compressive and tensile strain could be easily realized, so it is necessary to include the tensile strain case in our gain modeling program.

Figure Captions

Fig.1: Vertical near field distribution of a $Cd_{0.23}Zn_{0.77}Se$/ZnSe MQW blue green emitter (100Å/130Å, 10.5 periods, 0.24 μm total width, embedded in ZnSe).

Fig.2: Vertical far field distribution of a $Cd_{0.23}Zn_{0.77}Se$/ZnSe MQW blue green emitter (100Å/130Å, 10.5 periods, embedded in ZnSe): FWHM = 38°

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[2] R.W.H. Engelmann, C.L. Shieh, and C. Shu, "Multiquantum Well Lasers: Threshold Considerations." Book Chapter in 'Quantum Well Lasers', ed. P. Zory, Academic Press (in print).

[3] Y. Cai, R. Engelmann, and R. Raghuraman, "Simple model for carrier spill-over in quantum-well lasers consistent with local charge neutrality", OSA'92 Annual Meeting, Sept. 1992.

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[6] E.P. O'Reilly, G. Jones, A. Ghiti and A.R. Adams, "Improved performance due to suppression of spontaneous emission in tensile-strain semiconductor lasers", Electron. Lett. **27**, 1417 (1991).

[7] C. Trager-Cowan, P.J. Parbrook, B. Henderson and K.P. O'Donnell, "Band alignments in Zn(Cd)S(Se) strained layer superlattices", Semicond. Sci. Technol. **7**, 536-541 (1992).

[8] P. Zory, private communication, July 11, 1992.

Publications

R. Raghuraman, R. Engelmann and J.R. Arthur,
"Stripe-width and cavity-length dependent wavelength switching in gain-guided strained-layer InGaAs/GaAs single quantum well lasers"
Submitted for publication

Y. Cai and R. Engelmann,
"Proposal of novel blue-green laser diode based on ZnMgSeTe alloy system"
To be submitted for publication

Presentations

72. C. Zhao (speaker) and R Engelmann
"The trade-offs for high conversion efficiency in quasi-phase matched second harmonic generation."
Annual Meeting of the Oregon Academy of Science, Linfield College, McMinnville, OR, 27 Feb 1993.

73. Y. Cai (speaker) and R. Engelmann
"Proposal of novel blue green diode laser based on ZnMgSeTe alloy system."
Annual Meeting of the Oregon Academy of Science, Linfield College, McMinnville, OR, 27 Feb 1993.

Graduate Research Assistant Supported by URI

Y. Cai with R. Engelmann

Near Field Intensity of ZnCdSe/ZnSe (130/100 A X 10 MQW)

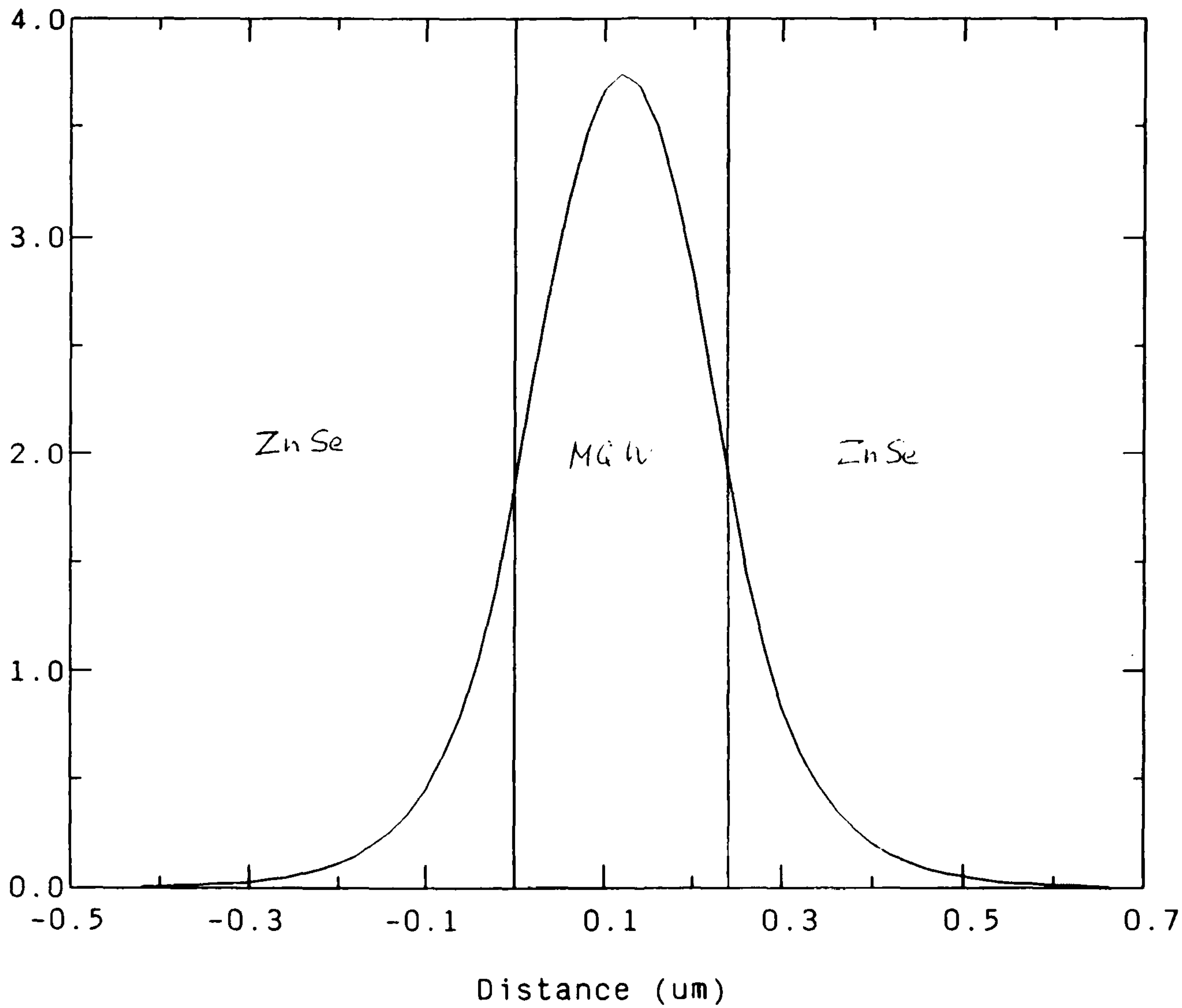

Fig. 1

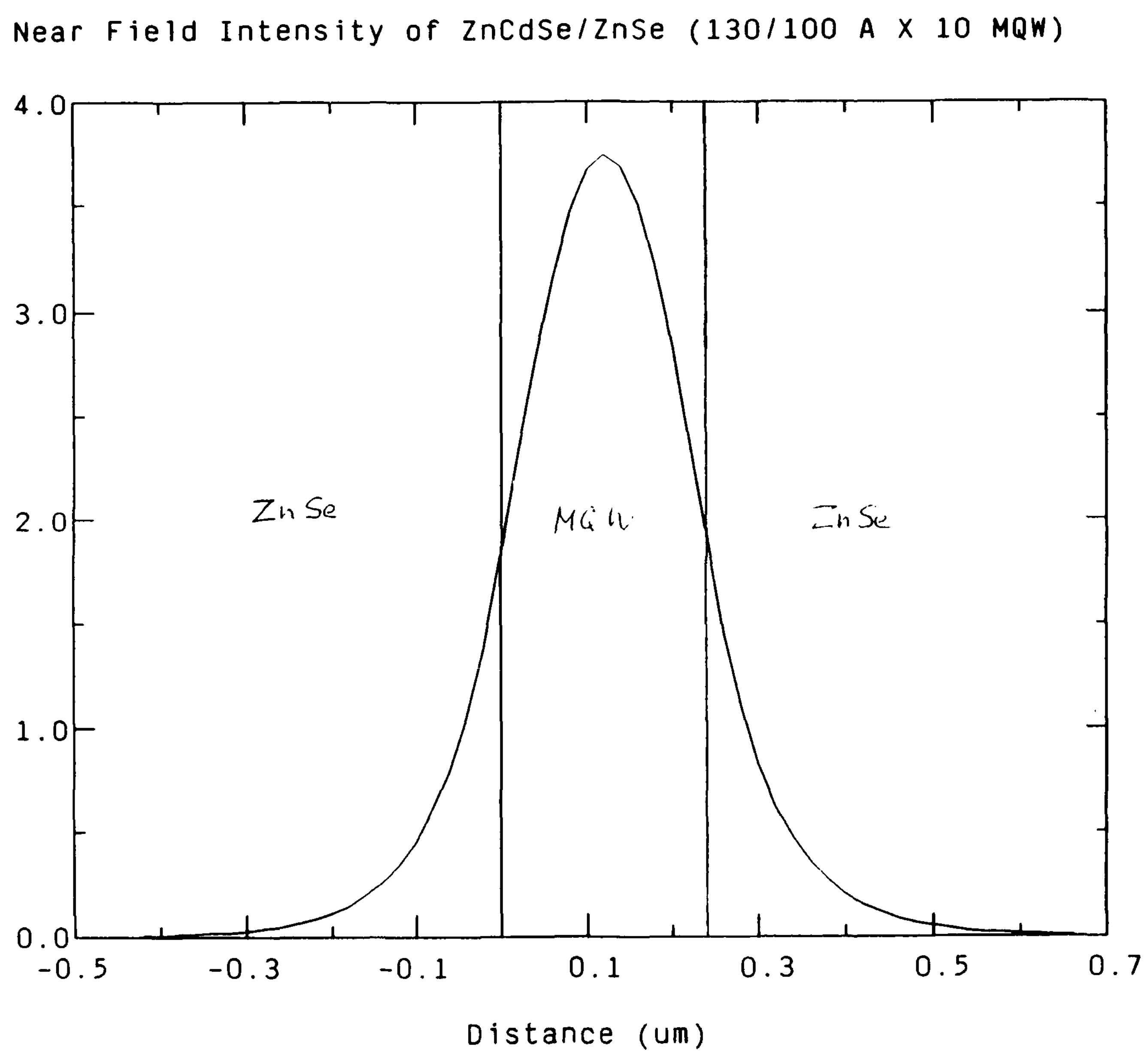
Near Field Intensity of ZnCdSe/ZnSe (130/100 A X 10 MQW)
4.0
3.0
2.0
1.0
0.0
-0.5
-0.3
-0.1
0.1
0.3
0.5
0.7
Distance (um)
ZnSe
MQW
ZnSe

Fig. 1

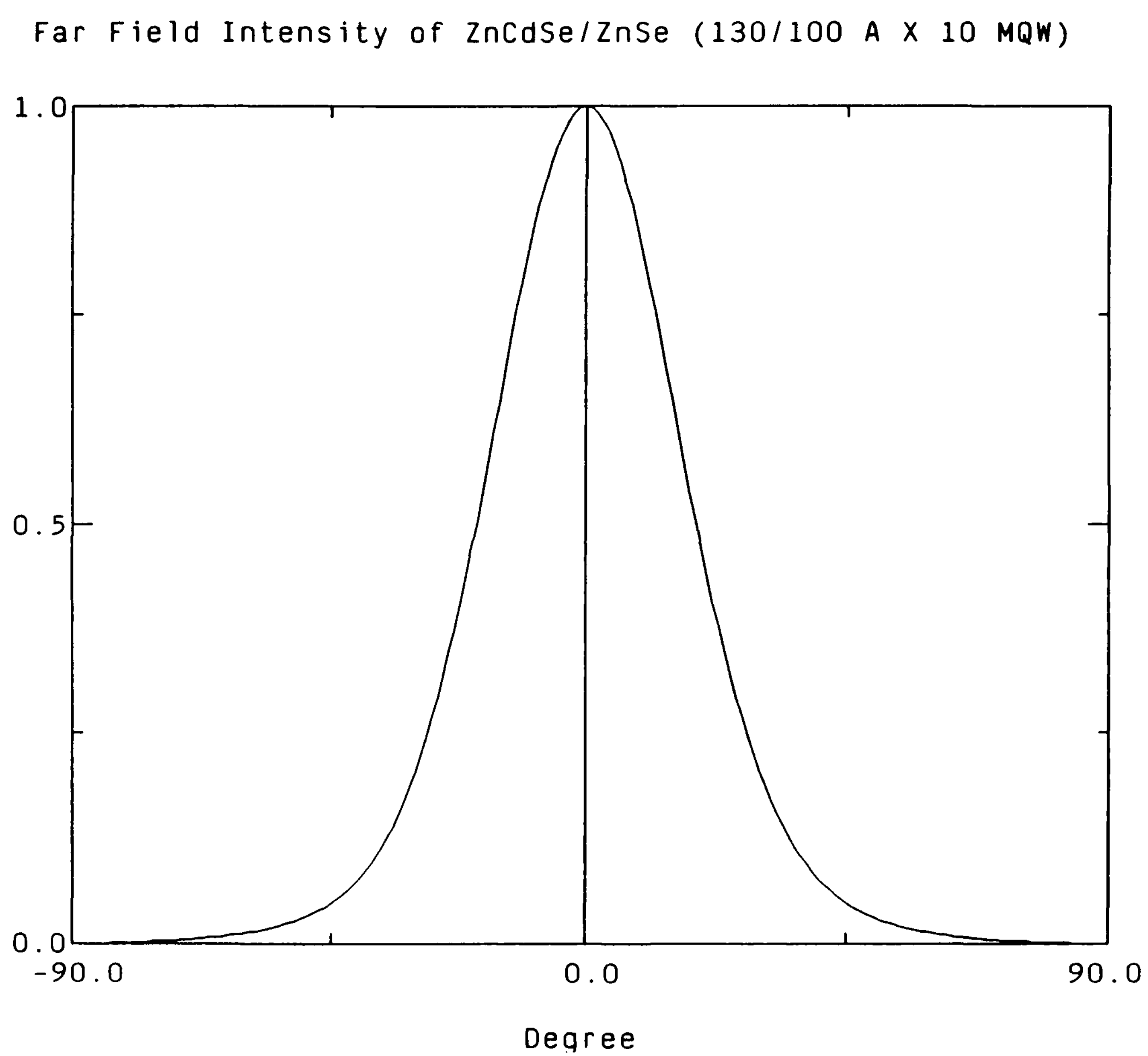
Far Field Intensity of ZnCdSe/ZnSe (130/100 A X 10 MQW)
1.0
0.5
0.0
-90.0
0.0
90.0
Degree

Fig. 2

(IX) SUBCONTRACT TO UNIVERSITY OF COLORADO (Jacques Pankove)

MOCVD Growth of Column III Nitrides

Third Quarterly Report on

GaN Part of DARPA-URI Project on Wide Bandgap Semiconductors for Short Wavelength Emitters

Award: UFLOR-OCG0845B

We grew many layers of GaN on $(1\bar{1}02)$ and (001) sapphire and on (100) Si. Mostly yellow or brown GaN layers were obtained. The coloring was attributed to O and/or C doping, and this was indeed verified by SIMS analysis (Figure 1). The carbon comes from the decomposition of the ethyls attached to Ga in TEG. The substitution of C for N produces a deep acceptor that renders GaN insulating. Finding the source of contaminating oxygen has been our greatest challenge.

Leak tests revealed a few air leaks that were promptly fixed, but the coloring recurred. Further leak tests with the substrate heater ON showed that thermally-induced stresses in the cold-wall system allowed air leakage at a gasket. This too could be fixed, but the coloring persisted. Ammonia was suspected. "Electronic grade" Matheson NH_3 appeared to have much less H_2O vapor (mass 18 on our residual gas analyzer [RGA]) than the "high-purity" Matheson NH_3. A Nanochem filter was installed that seemed effective in removing the mass 18 line. Still the coloring reappeared. We added H_2 to the reacting gases, we bubbled H_2 through TEG, . . . and the coloring remained. We changed TEG without getting clear GaN. The TEG used during air leaks was analyzed for contamination and found to be free of oxygen. Some samples were n-type very conducting; some were insulating. Weak photoluminescence was observed at 3.41 eV.

The difficulty in generating uniform layers of GaN was traced to the presence of surface regions that did not nucleate the growth of GaN. (See Figure 2.) To solve this problem will require experimentation with substrate surface treatment prior to growth.

Sometimes clusters of needle-shaped dendrites protruded from a nearly smooth GaN surface (Figure 3). In extreme cases, the dendrites formed sharply pointed conical needles about 5 μm long and about 0.3 μm in diameter at the base (Figure 4). Even a fur-like coating of GaN could be obtained (Figure 5). However, some uniform layers 10 μm thick were also produced.

X-ray diffraction measurements indicate that wurtzitic GaN has been grown. Figure 6 shows a typical x-ray diffraction spectrum of a GaN film deposited at 1050°C. The strong peak at 57.7° is due to the (1120) reflection from wurtzitic GaN, while the small peak at 52.6° corresponds to the (2024) reflection of the sapphire substrate.

We have concluded that the NH_3 flow rate is too low. Hence, a more powerful turbomolecular pump and a higher rate mass flow controller will be purchased and installed. This will permit increasing the V/III ratio for the GaN synthesis reaction. A new tank of ammonia from Scott will be installed. A bubbler of Mg CP_2 was ordered to start Mg doping as soon as the O/C contamination problem is solved.

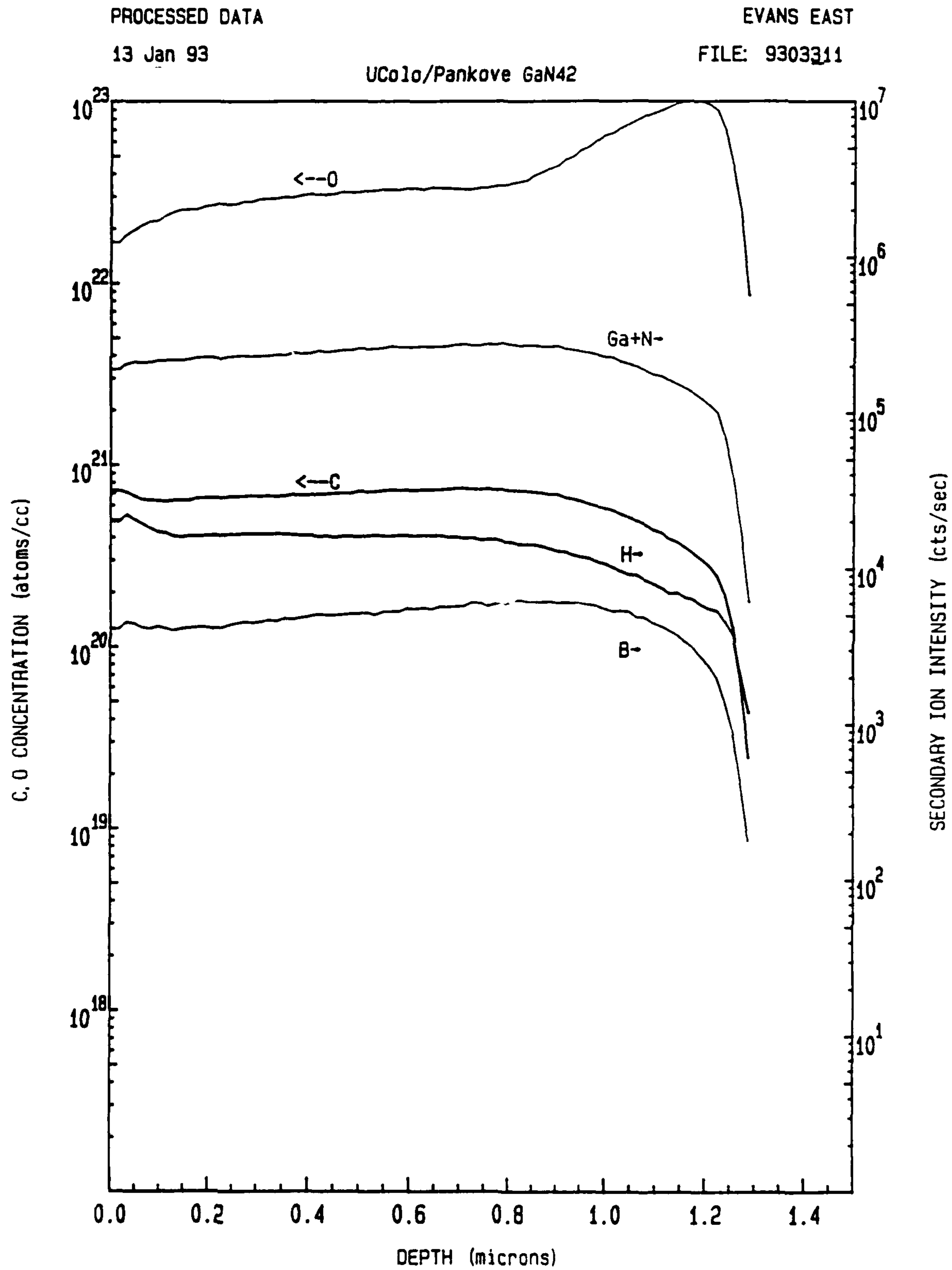

Figure 1. SIMS profiles of oxygen and carbon concentrations in sample GaN 42.

Figure 2. Cross-section of GaN layer grown on (0001) sapphire. Arrows show regions without nucleation.

Figure 3. Topographic view of GaN grown on (0001) sapphire showing clusters of dendrites.

Figure 4. Needle-like growth of GaN on $(1\bar{1}02)$ sapphire.

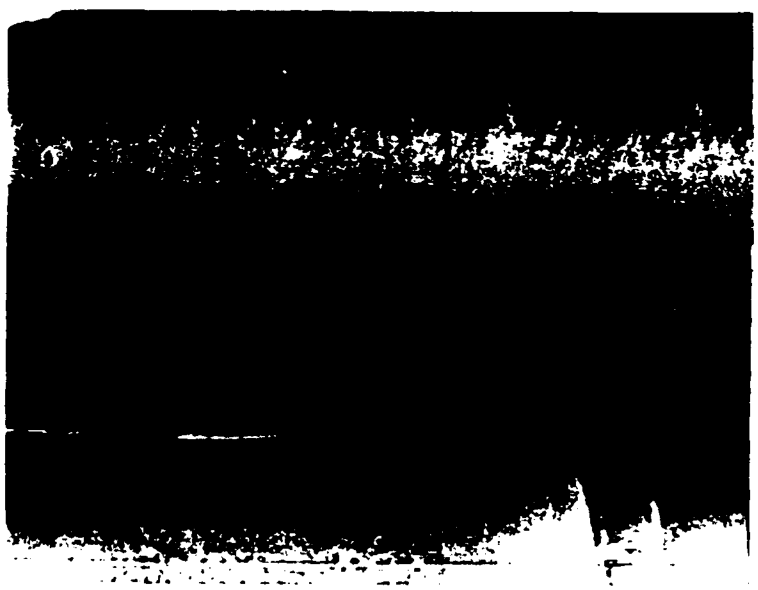

Figure 5. Fur-like growth of another GaN on $(1\bar{1}02)$ sapphire.

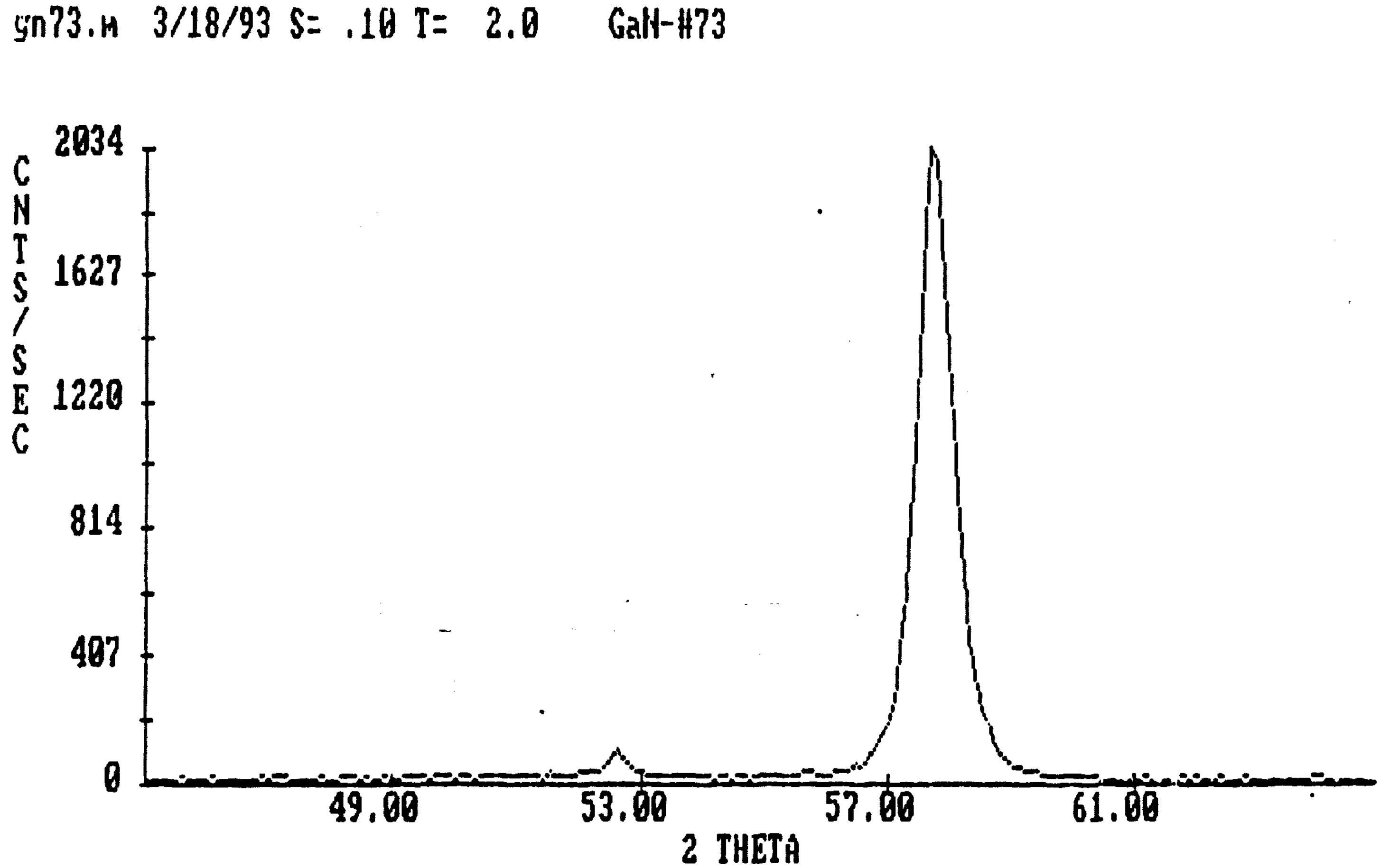

Figure 6. θ/2θ x-ray diffraction spectrum of GaN.

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